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## ADAPTIVE COMPENSATION METHOD FOR AN ANTI-LOCK BRAKE CONTROL

### TECHNICAL FIELD

This invention relates to motor vehicle anti-lock brake systems, and more particularly to a control method that adaptively adjusts an anti-lock brake pressure apply rate to compensate for a detected degradation of  
5 braking effectiveness.

### BACKGROUND OF THE INVENTION

A motor vehicle anti-lock braking system (referred to herein as an ABS system) repeatedly releases and re-applies hydraulic brake pressures  
10 during conditions of wheel lock with the objective of maximizing the tractive force between the vehicle tires and the road surface. However, the control strategies assume that the brake system is operating normally, and the system performs at a sub-optimal level when the braking effectiveness is degraded due to fluid leakage, fading, poor adjustment, wear, and so forth.  
15 Accordingly, what is needed is an anti-lock brake control method that adaptively compensates for degraded braking effectiveness.

### SUMMARY OF THE INVENTION

The present invention is directed to an improved anti-lock control  
20 method for a vehicle brake system, wherein various factors that degrade the effectiveness of the brake system are identified and used to adaptively determine a brake apply rate during anti-lock brake control. In the illustrated embodiment, the identified factors include fading due to brake heating, hydraulic leakage, mis-adjusted and non-releasing rear brakes,  
25 brake wear and excessive vehicle weight, and the adaptively-determined brake apply rate compensates for the identified brake system degradation so

that the optimal tractive force during anti-lock brake control is more nearly realized.

## BRIEF DESCRIPTION OF THE DRAWINGS

5           Figure 1 is a schematic diagram of a vehicle braking system, including a brake pedal position sensor, and a microprocessor-based control unit programmed to carry out the control method of this invention.

          Figure 2 is a graph depicting vehicle deceleration as a function of brake pedal position for the braking system of Figure 1.

10           Figure 3 is a graph depicting exemplary calibration brake effectiveness table data developed by the control unit of Figure 1.

          Figure 4 is a graph depicting exemplary current brake effectiveness table data developed by the control unit of Figure 1.

          Figures 5, 6, 7 and 8 together depict a flow diagram of a first  
15 software routine executed by the control unit of Figure 1 for identifying factors that degrade the braking system effectiveness.

          Figures 9 and 10 together depict a flow diagram of a second software routine executed by the control unit of Figure 1 for adaptively adjusting the brake apply rate during anti-lock brake control based on the  
20 factors identified by the routine of Figures 5, 6, 7 and 8.

## DESCRIPTION OF THE PREFERRED EMBODIMENT

          Referring to Figure 1, the present invention is disclosed in the context of an anti-lock braking system 10 for a vehicle 12 having  
25 hydraulically activated friction brakes 14, 16, 18, 20 at each of four vehicle wheels 22, 24, 26, 28. In mechanizations where the rear brakes 18, 20 are drum brakes, a self-adjusting mechanism (not shown) is included to compensate for brake shoe wear during braking while the vehicle 12 is backing up. A driver-manipulated brake pedal 30 is mechanically coupled to  
30 a master cylinder (MC) 32 for producing hydraulic pressure in proportion to

the force applied to pedal 30. Master cylinder 32, which may include a pneumatic booster (not shown), proportions the hydraulic pressure between front and rear brake supply lines 34 and 36 in a conventional manner. Front supply line 34 is coupled to the left front service brake 14 via left-front anti-lock modulator (M) 38, and to the right front service brake 16 via right-front anti-lock modulator (M) 40. Rear supply line 36 is coupled to the left and right rear wheel brakes 18, 20 via rear anti-lock modulator (M) 42.

A microprocessor-based control unit 50 receives various inputs, including wheel speed signals on lines 52, 54, 56, 58 from respective wheel speed sensors 60, 62, 64, 66 and a brake pedal position signal PP on line 68 from pedal position sensor 70. The sensors 60, 62, 64, 66 and 70 may be implemented with conventional devices in a manner known to those skilled in the art. In response to the various inputs, the control unit 50 outputs modulator control signals on lines 72, 74, 76 during wheel lock-up conditions, and diagnostic information signals on line 80 for display on a driver information device 82.

In general, the control unit 50 monitors the measured wheel speeds to detect a condition of insipient wheel lock, and then controls modulators 38, 40, 42 to effect a rapid initial reduction in the respective brake pressures for essentially eliminating wheel slip, and then to repeatedly release and re-apply the respective brake pressures with the objective of maximizing the tractive force between the vehicle tires and the road surface. Of course, the optimal values of anti-lock control parameters such as the pressure apply rate vary with the effectiveness of the braking system. Ordinarily, however, anti-lock brake control systems assume nominal braking system effectiveness, and the braking performance is degraded to the extent that the assumption is wrong. For example, if the brakes are exhibiting fading due to heating, less brake torque will result for a given brake pressure command. Thus, the performance of the anti-lock control could be improved if the braking system characteristics were known. For

example, if the brakes are exhibiting fading, the pressure apply rate during wheel lock conditions could be increased to compensate for the fading and more nearly realize the optimal tractive force. This issue is addressed by the present invention, which identifies various factors that degrade the effectiveness of the brake system 10 and adaptively adjusts the pressure apply rate during anti-lock brake control so as to compensate for the identified factors. In the illustrated embodiment, the identified factors include fading due to brake heating, hydraulic leakage, mis-adjusted and non-releasing rear brakes, brake wear and excessive vehicle weight.

In the illustrated embodiment, the braking system degradation factors are identified by determining a base or calibration relationship between brake pedal position and vehicle deceleration for defined vehicle braking operation, periodically determining a current relationship, and comparing the current and calibration relationships.

Figure 2 graphically depicts a representative relationship between vehicle deceleration and brake pedal position for defined braking of the vehicle 12, assuming that there is no lock-up condition and the modulators 38, 40, 42 are inactive. Typically, the "knee" portion of the relationship varies considerably from stop to stop, whereas the portion of the relationship above the knee tends to be linear and repeatable from stop to stop. For this reason, the knee portion of the relationship is ignored for purposes of characterizing braking effectiveness, and the brake pedal position vs. vehicle deceleration relationship is characterized only for pedal positions and vehicle decelerations in the linear portion above the knee. In the illustrated embodiment, for example, the data collection is carried out by determining the pedal position corresponding to three different vehicle deceleration values identified in Figure 2 as D1, D2 and D3. Of course, any number of data points may be used, and the data points may be defined in terms of pedal position, if desired. In any case, the braking data is only collected during braking operation when the pedal 30 is depressed at a "normal" rate or held

at an essentially static position; data is not collected upon release of the pedal  
30 nor during panic braking. This eliminates the need to compensate for the  
effects of suspension and powertrain dynamics, tire and sensor dynamics,  
and so on. The vehicle acceleration at the onset of braking is saved and  
5 subtracted from the deceleration during braking operation in order to  
compensate for the effects of engine braking and road grade. Of course, the  
road grade and other factors such as vehicle weight and the effects of brake  
heating may be estimated and used to compensate the collected braking data;  
see for example, the U.S. Patent No. 6,212,458 to Walenty et al., issued on  
10 April 3, 2001, and incorporated herein by reference. Figure 3 graphically  
depicts representative calibration table data for the vehicle 12, whereas  
Figure 4 graphically depicts representative current table data. It will be  
noted that the pedal position values stored in the calibration table are  
identified as PPCAL1, PPCAL2 and PPCAL3, whereas the pedal position  
15 values stored in the current brake effectiveness table are identified as  
PPCUR1, PPCUR2 and PPCUR3.

Once the calibration and current data tables have been  
constructed, a series of diagnostic tests are carried out to identify degraded  
braking effectiveness and the likely cause. In general, the calibration table is  
20 used to define an expected vehicle deceleration for any brake pedal position  
above the minimum pedal position table entry. When the actual vehicle  
deceleration (compensated for grade, weight, etc.) is much lower than the  
expected value, hydraulic leaking, brake fading or air in the brake lines is  
indicated. Of these conditions, an estimate of brake heating is used to  
25 distinguish brake fading from hydraulic leaks and air in the hydraulic brake  
lines. Non-adjustment of the rear brakes 18, 20 is detected by computing a  
speed difference SPD\_DELTA between the front and rear wheels and  
comparing it to a pedal position dependent threshold. If the speed difference  
exceeds the threshold by a calibration amount for at least a predefined time  
30 interval, poor adjustment of the rear brakes 18, 20 is indicated.

Additionally, brake wear is detected by comparing the brake pedal positions in the current table with the corresponding pedal positions in the calibration table.

The flow diagram of Figures 5-8 depicts a first software routine that is periodically executed by control unit 50 of Figure 1 for identifying the above-mentioned brake system degradation factors. In general, the flow diagram comprises an input processing block 90, a leak/fade detection portion consisting of blocks 96-116, a data collection portion consisting of blocks 120-126 and 150-174, a rear brake adjustment test consisting of blocks 130-146, a brake wear test consisting of blocks 180-216, and a condition warning portion consisting of blocks 218-220.

Referring to Figure 5, the input processing block 90 is first executed to read the brake pedal position PP and the wheel speeds, to compute the vehicle acceleration ACCEL (compensated for road grade and vehicle weight) and the front-to-rear speed delta SPD\_DELTA, and to update an estimate of the brake temperature BRAKE\_HEAT. Also, the vehicle acceleration when the brake pedal is initially depressed is saved as the onset acceleration ACCEL\_ONSET, and a number of other brake-related parameters such as road grade, vehicle weight and the brake heat may be estimated as described, for example, in the aforementioned U.S. Patent No. 6,212,458 to Walenty et al. The brake temperature term BRAKE\_HEAT can be modeled reasonably well, and is updated as follows:

$$\begin{aligned} \text{BRAKE\_HEAT} = & \text{BRAKE\_HEAT} - ((\text{VSPD} + \text{K1})^2 * \text{K2}) * \\ & (\text{BRAKE\_HEAT} - (\text{BRAKE\_HEAT} * \text{Tamb}) + \\ & (\text{BRAKE\_TQ} * \text{Kheat} * \text{VSPD}) * (\text{K3} - \text{BRAKE\_HEAT}) / \text{K3} \end{aligned} \quad (1)$$

where K1, K2 and K3 are constants, Tamb is the ambient temperature, and VSPD is the vehicle speed.

The block 92 determines if the calibration mode is in effect by checking the status of a CAL MODE FLAG. The CAL MODE FLAG is set to true to activate the calibration mode when the vehicle is new, and thereafter each time the braking system 10 is serviced. Thus, block 92 will initially be answered in the affirmative, signaling the execution of blocks 120-126, as indicated by the circled letter A, to determine if the braking condition is "normal" for purposes of brake data collection. Otherwise, the blocks 96-116 are executed to carry out the leak/fade detection test, provided that  $PP > PPCUR1$ , as determined at block 94.

Referring to Figure 6 and the data collection portion of the routine, the blocks 120-126 are first executed to determine if the current braking activity is suitable for data collection. Block 120 determines if ACCEL exceeds a relatively high threshold acceleration Kaccel, block 122 determines if the previous pedal position PPold is greater than the current value PP, block 124 determines if the difference ( $PP - PPold$ ) exceeds a threshold rate Krate, and block 126 determines if the difference ( $ACCEL - ACCEL\_ONSET$ ) is less than the minimum deceleration table entry D1. Each of the blocks 120, 122, 124 and 126 must be answered in the negative to proceed with data collection; thus, a "normal" braking condition is defined as one in which (1)  $ACCEL < Kaccel$ , (2)  $PPold < PP$ , (3)  $PP - PPold < Krate$ , and (4)  $ACCEL - ACCEL\_ONSET > D1$ . Stated oppositely, "normal" braking for purposes of data collection does not include (1) panic braking, (2) high rate brake pedal movement, (3) brake pedal releasing, or (4) deceleration below the linear range of the deceleration vs. pedal position relationship. If at least one of the blocks 120-126 is answered in the affirmative, the routine is exited, as indicated. If all are answered in the negative, the current braking activity is considered to be suitable for data collection, and if block 128 determines that the CAL MODE FLAG is true, the control unit proceeds to block 150, as indicated by the circled letter B. Otherwise, the blocks 132-146 are executed to carry out

the rear brake adjustment test, provided that  $PP > PPCUR1$ , as determined at block 130.

The data collection blocks 150-174 identify the brake pedal positions P1, P2, P3 corresponding to the respective predefined vehicle  
 5 deceleration values D1, D2, D3, and construct current and calibration tables corresponding to those depicted in Figures 3 and 4. The blocks 150, 154 and 160 respectively determine if the pedal positions P1, P2 and P3 have been identified, based on the status of the D1 FLAG, the D2 FLAG and the D3 FLAG. If block 150 determines that the D1 FLAG is not true, the block  
 10 151 determines if the difference ( $ACCEL - ACCEL\_ONSET$ ) has reached the predefined deceleration value identified in Figure 3 as D1. If not, the routine is exited; if so, the block 152 sets the D1 FLAG to true, and uses the current value of PP to update the pedal position variable P1 as shown. On the next execution of the routine, block 150 will be answered in the  
 15 affirmative, and block 154 will determine if the D2 FLAG is true. If not, the block 156 determines if the difference ( $ACCEL - ACCEL\_ONSET$ ) has reached the predefined deceleration value identified in Figure 3 as D2. If not, the routine is exited; if so, the block 158 sets the D2 FLAG to true, and uses the current value of PP to update the pedal position variable P2 as  
 20 shown. On the next execution of the routine, blocks 150 and 154 will both be answered in the affirmative, and block 160 will determine if the D3 FLAG is true. If not, the block 162 determines if the difference ( $ACCEL - ACCEL\_ONSET$ ) has reached the predefined deceleration value identified in Figure 3 as D3. If not, the routine is exited; if so, the block 164 sets the D3  
 25 FLAG to true, uses the current value of PP to update the pedal position variable P3, increments a brake event counter BEC\_CTR, and sums the pedal position variables P1, P2 and P3 with corresponding position summation values PS1, PS2 and PS3. However, if the difference ( $ACCEL - ACCEL\_ONSET$ ) for the braking event fails to reach the deceleration value  
 30 D3, the block 164 is not executed, and any pedal position data collected is



discarded. After each successful data collection, the block 166 compares the brake event counter BEC\_CTR to a calibrated threshold K\_BEC indicative of the number of braking events needed to construct a current deceleration vs. pedal position table. Thus, when BEC\_CTR reaches K\_BEC, the identified  
5 pedal position variables P1, P2, P3 for K\_BEC (which may have a value of ten, for example) braking events will have been accumulated in the respective position summation values PS1, PS2, PS3. When this happens, the block 168 is executed to calculate average pedal position values by dividing the respective position summation values PS1, PS2, PS3 by the  
10 brake event counter BEC\_CTR, and to update the current deceleration vs. pedal position table using the calculated values. In other words, PPCUR1 = PS1/BEC\_CTR, PPCUR2 = PS2/BEC\_CTR and PPCUR3 = PS3/BEC\_CTR. Since changes in the vehicle weight change the current characterization table data, the vehicle weight is also updated according to:

$$15 \quad V\_WT = V\_WT(\text{last}) + WT\_DELTA \quad (2)$$

where WT\_DELTA is a measure of the change in characterization data, compensated for changes in brake temperature. Specifically, WT\_DELTA is  
20 given by the expression:

$$\begin{aligned} WT\_DELTA = & [(((PPCUR3old - PPCUR1old) - (PPCUR3 - PPCUR1))/ \\ & (D3-D1)) * Kwt] + (UPDATE\_BRAKE\_HEAT - \\ & BRAKE\_HEAT) * Kheat \end{aligned} \quad (3)$$

25 where Kwt and Kheat are constants, PPCUR1old and PPCUR3old are old table values, and UPDATE\_BRAKE\_HEAT is the value of BRAKE\_HEAT when the characterization table was previously updated. Block 168 also resets the brake event counter BEC\_CTR and the position summation values  
30 PS1, PS2, PS3 to zero, and increments a current table update counter

CTU\_CTR. If the CAL MODE FLAG is set, as determined at block 170, the block 172 compares the current table update counter CTU\_CTR to a calibrated threshold K\_CTU (which may have a value of fifty, for example), where the product ( $K_{BEC} * K_{CTU}$ ) is the number of braking events  
5 needed to construct the calibration deceleration vs. pedal position table. Thus, when block 172 is answered in the affirmative, the block 174 is executed to transfer the pedal position values of the current deceleration vs. pedal position table into the calibration pedal position table, to set the CAL MODE FLAG to false, and to reset the current table update counter  
10 CTU\_CTR to zero. Once the CAL MODE FLAG has been set to false, the data collection blocks 150-168 will continue to be executed for the purpose of periodically updating the current deceleration vs. pedal position table, after which block 170 will be answered in the negative, enabling execution of the brake wear test portion of the routine (blocks 180-216).

15 The leak/fade test portion of the routine (blocks 96-116) is initialized at block 96 by computing a deceleration loss term DECEL\_LOSS based on the current pedal position PP, the calibration deceleration vs. pedal position table, ACCEL\_ONSET, and ACCEL. The amount by which PP exceeds PPCUR1 is used to determine an expected vehicle deceleration from  
20 the calibration table, which should be essentially equal to the difference ( $ACCEL - ACCEL\_ONSET$ ) when the braking effectiveness is unimpaired. However, when the braking effectiveness is impaired, the expected vehicle deceleration will be greater than ( $ACCEL - ACCEL\_ONSET$ ), so that DECEL\_LOSS provides a measure of braking degradation. If  
25 DECEL\_LOSS exceeds a threshold KLOSS, as determined at block 98, the blocks 100 and 102 increment a deceleration loss counter DL\_CTR unless the count has reached a calibrated threshold KLOSS\_CNT. Once DL\_CTR reaches KLOSS\_CNT -- that is, once DECEL\_LOSS has exceeded KLOSS for a calibrated time -- block 100 is answered in the negative, and blocks  
30 104-108 are executed to determine if the impaired braking effectiveness is

due to a hydraulic leak or brake fading. If the estimated brake heat exceeds a calibrated value KFADE (corresponding to a brake temperature of 500 degrees C., for example), as determined at block 104, the block 106 is executed to set a BRAKE FADE FLAG. Otherwise, the block 108 is executed to set a BRAKE FLUID LEAK FLAG. If DECEL\_LOSS is less than or equal to KLOSS, and DL\_CTR is zero, the block 112 resets the BRAKE FADE FLAG and the BRAKE FLUID LEAK FLAG. If DL\_CTR is greater than zero, and DECEL\_LOSS is less than a calibrated threshold KHR which is lower than KLOSS, the block 116 decrements DL\_CTR.

Thus, if the deceleration due to braking is less than the expected deceleration by at least a predefined amount (KLOSS) for at least a predefined time (defined by KLOSS\_CNT), the BRAKE FADE FLAG or the BRAKE FLUID LEAK FLAG is set to indicate the respective brake system failure.

The rear brake adjustment test portion of the routine (blocks 132-146) involves comparing the front-to-rear speed delta SPD\_DELTA to pedal position dependent threshold THR\_DELTA, defined as  $(PP - PPCUR1) * K_{gain}$ , where  $K_{gain}$  is a predefined gain factor. As either or both of the rear wheel brakes 18, 20 go out of adjustment, SPD\_DELTA will become more and more negative, and when the sum of SPD\_DELTA and THR\_DELTA falls below a threshold Knonadj, as determined at block 132, the blocks 134 and 136 increment a non-adjusting rear counter NAR\_CTR unless the count has reached a calibrated threshold KNAR\_CNT. Once NAR\_CTR reaches KNAR\_CNT – that is, the sum of SPD\_DELTA and THR\_DELTA falls below a threshold Knonadj for a calibrated time – block 134 is answered in the affirmative, and blocks 138 is executed to set the NON\_ADJUSTED REAR BRAKE FLAG. The block 146 decrements NAR\_CTR whenever when the sum of SPD\_DELTA and THR\_DELTA exceeds the threshold Kadj, and the blocks 140-142 reset the NON\_ADJUSTED REAR BRAKE FLAG when NAR\_CTR is zero.

The brake wear test portion of the routine (blocks 180-216) essentially determines if the brake pedal 30 must be depressed further than normal to achieve a given vehicle deceleration by comparing the pedal positions of the just-constructed current deceleration vs. pedal position table with the corresponding pedal positions from the calibration table. If the pedal position values from the current table exceed the corresponding values from the calibration table by predefined calibration amounts, a brake wear counter BW\_CTR is incremented. Thus, blocks 180-182 increment BW\_CTR if  $(PPCUR1 - PPCAL1) > KBW1$ , blocks 190-192 increment BW\_CTR if  $(PPCUR2 - PPCAL2) > KBW2$ , and blocks 200-202 increment BW\_CTR if  $(PPCUR3 - PPCAL3) > KBW3$ , where KBW1, KBW2 and KBW3 are the predefined calibration amounts. If the pedal position values from the current table are within a calibration amount of the pedal position values from the current table, the brake wear counter BW\_CTR is decremented by Kdec if BW\_CTR is not already zero. Thus, blocks 184, 186, 188 decrement BW\_CTR toward zero if  $(PPCUR1 - PPCAL1) < KNBW1$ , blocks 194, 196, 198 decrement BW\_CTR toward zero if  $(PPCUR2 - PPCAL2) < KNBW2$ , and blocks 204, 206, 208 decrement BW\_CTR toward zero if  $(PPCUR3 - PPCAL3) < KNBW3$ , where KNBW1, KNBW2 and KNBW3 are calibration amounts indicative of no brake wear. If the execution of blocks 180-208 results in a BW\_CTR value of zero, as determined at blocks 206 and 210, the block 212 is executed to reset the BRAKE WEAR FLAG. On the other hand, if bloc 214 determines that BW\_CTR exceeds a threshold KBWEAR, the block 216 sets the BRAKE WEAR FLAG.

Finally, the blocks 218 and 220 are executed to check the brake condition flags, and to display messages corresponding to set flags on the driver information device 82, and to initiate other responses such as an aggressive downshift schedule that supplements the vehicle deceleration due to application of the service brakes.

The flow diagram of Figures 9-10 depicts an ABS control routine that is periodically executed by the controller 50 of Figure 1, and that is responsive to the brake system flags and other parameters developed in the flow diagram of Figures 5-8. Referring to Figure 9, the block 230 is first executed to read the brake pedal position PP, the wheel speeds WS1-WS4, and the brake flags, and to update the wheel slip values (SLIP). Block 232 then checks the ABS FLAG to determine if anti-lock braking is active. If insipient wheel lock has already been detected, and the modulators 38, 40, 42 have been activated to modulate the brake pressure, the ABS FLAG will be TRUE; in this case, the block 270 of Figure 10 is executed for carrying out the ABS control algorithm for repeatedly releasing and re-applying brake pressure to maximize braking tractive force. Ordinarily, however, the ABS FLAG is FALSE, and if the pedal position PP exceeds the lowest position PPCUR1 of the current brake characterization table (as determined at block 234), the block 236 is executed to determine the braking torque BRAKE\_TQ, the road surface coefficient of friction SURFACE\_MU, and the road grade GRADE. The brake torque BRAKE\_TQ is estimated based on the pedal position PP and the current brake characterization table values as follows:

$$\text{BRAKE\_TQ} = [((\text{PP} - \text{PPCUR1}) * (\text{PPCUR3} - \text{PPCUR1}) / (\text{D3} - \text{D1})) * \text{Kbt}] + (\text{UPDATE\_BRAKE\_HEAT} - \text{BRAKE\_HEAT}) * \text{Kheat} \quad (4)$$

where Kbt and Kheat are constants, and UPDATE\_BRAKE\_HEAT is the estimated brake temperature BRAKE\_HEAT when the characterization table was last updated. The road surface coefficient of friction SURFACE\_MU is given by:

$$\text{SURFACE\_MU} = (\text{BRAKE\_TQ} / \text{V\_WT}) * \text{Kmu} \quad (5)$$

where  $K_{mu}$  is a constant. Finally, the road grade (GRADE) is estimated according to the expression:

$$\text{GRADE} = \text{ROLL\_RES} + \text{AERO\_DRAG} + \text{ENG\_BR} + \text{BRAKE\_TQ} + \text{ACCEL} \quad (6)$$

where ROLL\_RES is the rolling resistance, AERO\_DRAG is the aerodynamic drag, ENG\_BR is the engine braking torque, and ACCEL is the vehicle acceleration.

If incipient wheel lock is detected, as determined at block 238, the block 240 sets the ABS FLAG, and the block 242 computes initial brake pressure release values IPRfrt, IPRrear for the front and rear wheels as follows:

$$\text{IPRfrt} = \text{PRmax\_f} * (1 - \text{SURFACE\_MU} - (\text{GRADE} * \text{Kwt\_tr\_f})) \quad (7)$$

$$\text{IPRrear} = \text{PRmax\_r} * (1 - \text{SURFACE\_MU} - (\text{GRADE} * \text{Kwt\_tr\_r})) \quad (8)$$

where PRmax\_f and PRmax\_r are the maximum front and rear initial release pressures, and Kwt\_tr\_f and Kwt\_tr\_r are front and rear weight transfer constants. Additionally, a normal value of the brake pressure apply rate PR\_APPLY\_RATE for ABS control is computed as a function of SURFACE\_MU.

If the BRAKE FADE FLAG is set, as determined at block 244, the degraded braking biases the term SURFACE\_MU to an artificially low value, and block 246 computes a corrected coefficient of friction SURFACE\_MU' as follows:

$$\text{SURFACE\_MU}' = \text{SURFACE\_MU} - [(\text{Kn bh} - \text{BRAKE\_HEAT}) * \text{Kheat}] \quad (9)$$

where Knbh is a nominal brake heat value, and Kheat is a normalizing constant. The brake pressure apply rate PR\_APPLY\_RATE is normally proportional to SURFACE\_MU as mentioned in reference to block 242, but in the case of brake fading, PR\_APPLY\_RATE must be increased to develop the desired brake torque. Thus, block 248 re-computes the brake pressure apply rate PR\_APPLY\_RATE based on the amount of detected fading, as follows:

$$\text{PR\_APPLY\_RATE} = \text{SURFACE\_MU}' * [(\text{Knbh} - \text{BRAKE\_HEAT}) * \text{Kfade}] \quad (10)$$

where Kfade is a normalizing constant. Although increasing PR\_APPLY\_RATE may increase the fading, it will also increase the braking effectiveness, allowing the vehicle to stop as soon as possible.

If the BRAKE FLUID LEAK FLAG is set, as determined at block 250, the blocks 252, 254 and 256 are executed to estimate the extent of the leak, to revise SURFACE\_MU, and to compute a PR\_APPLY\_RATE value that will compensate for the detected leakage. Block 252 estimates the extent of the leak by incrementing a counter value TIME\_SET and computing a LEAK\_RATE term according to the product of TIME\_SET and a pressure constant Kpress. As with brake fading, fluid leakage causes the road coefficient of friction term SURFACE\_MU computed at block 236 to be too low, and block 254 computes a corrected coefficient of friction SURFACE\_MU' as follows:

$$\text{SURFACE\_MU}' = \text{SURFACE\_MU} - (\text{LEAK\_RATE} * \text{Kleak}) \quad (11)$$

where Kleak is a normalizing constant. The brake pressure apply rate PR\_APPLY\_RATE is normally proportional to SURFACE\_MU, but in the case of fluid leakage, PR\_APPLY\_RATE must be increased to develop the

desired brake torque. Thus, block 256 re-computes the brake pressure apply rate  $PR\_APPLY\_RATE$  based on the amount of detected fluid leakage, as follows:

$$5 \quad PR\_APPLY\_RATE = SURFACE\_MU' * (LEAK\_RATE * K_{ramp}) \quad (12)$$

where  $K_{ramp}$  is a normalizing constant. Although increasing  $PR\_APPLY\_RATE$  may increase the fluid leakage, it will also increase the braking effectiveness, allowing the vehicle to stop as soon as possible.

10           If the NON-ADJUSTED REAR BRAKE FLAG is set, as determined at block 258, the block 260 is executed to revise  $SURFACE\_MU$ , and to compute a  $PR\_APPLY\_RATE$  value for the respective rear brake that will compensate for the misadjustment. Specifically, the corrected coefficient of friction  $SURFACE\_MU'$  and

15  $PR\_APPLY\_RATE$  are determined as follows:

$$SURFACE\_MU' = SURFACE\_MU - (SPD\_DELTA * K_{nar}) \quad (13)$$

$$PR\_APPLY\_RATE = SURFACE\_MU' * (SPD\_DELTA * K_{nar}) \quad (14)$$

20   where  $SPD\_DELTA$  is the front-to-rear speed delta determined at block 90 of Figure 5, and  $K_{nar}$  is a normalizing constant.

Another possible rear brake problem is a non-releasing rear brake shoe. If this condition is detected, the pressure apply rate may be increased on the opposite rear brake, or both rear brakes may be released during ABS

25   operation. The non-releasing rear brake influences the calculated front-to-rear speed delta  $SPD\_DELTA$ , and if the pressure apply rate is increased on the opposite rear brake, the apply rate may be computed essentially as explained above in respect to the non-adjusted rear brake condition, only with a different normalizing constant.



If the BRAKE WEAR flag is set, as determined at block 262, the block 264 is executed to increase the PR\_APPLY\_RATE value to compensate for the brake wear. Specifically, PR\_APPLY\_RATE is determined as follows:

5

$$\text{PR\_APPLY\_RATE} = \text{SURFACE\_MU} * \text{Kwear} \quad (15)$$

where Kwear is a predetermined constant.

Finally, if the determined vehicle weight V\_WT exceeds a reference weight WT\_REF, as determined at block 266, block 268 is executed to augment the pressure apply rate PR\_APPLY\_RATE as follows:

$$\text{PR\_APPLY\_RATE} = \text{SURFACE\_MU} * (\text{V\_WT} - \text{Klvw}) * \text{Kwt} \quad (16)$$

where Klvw is the normally loaded vehicle weight, and Kwt is a gain constant.

In summary, the control of this invention adjusts anti-lock brake control parameters to adaptively compensate for identified brake degradation factors, such as fading, fluid leakage, brake wear, and excessive vehicle weight. While described in reference to the illustrated embodiment, it is expected that various modifications in addition to those mentioned above will occur to those skilled in the art. For example, the control is applicable to other types of anti-lock brake systems, and other types of vehicles, including electric or hybrid-electric vehicles that utilize regenerative braking to decelerate the vehicle. Also, the control methodology may include logic for selecting the desired pressure apply rate if two or more of the brake diagnostic flags are set. Thus, it will be understood that the scope of this invention is not limited to the illustrated embodiment, and that diagnostic methods incorporating these and other modifications may fall within the scope of this invention, which is defined by the appended claims.